

Dignosis of Pulley-Belt System Faults Using Vibration Analysis Technique

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Abstract

This work presents the pulley-belt system faults like unbalance, misalignment, belt worm and resonance. Which dedicated by vibration analysis technique, this system built and an experimental results had been obtained to find out the types of faults that appeared in the manufactured system. A selected faults have been created where the resulted dynamic response has been analyzed. The vibration results obtained by manufactured system by sensors ADXL335 (3-axis accelerometer) mounted on bearing brackets of drive and driven shafts. These sensors connected to Arduino type mega 2560 (microcontroller) which sending the data of vibration to the laptop in order to display it in Sigview software as a time and frequency domain band by FFT (fast Fourier transform). The results of FFT explained the effect of each type of faults comparing with the optimum condition FFT of the system.

Key words: Vibration analysis, FFT, Diagnosis fault, Optimal condition.

الخلاصة

يقدم هذا العمل عيوب منظومة البكرة-الحزام مثل (انعدام التوازن ، عدم التحاذي ، تلف في الحزام.....الخ) والتي شخصت عن طريق أسلوب التحليل الاهتزازي. هذه المنظومة بنيت واستخرجت النتائج العملية وحلت لأيجاد أنواع العيوب التي ظهرت في المنظومة المصنعة. تم خلق مجموعة من العيوب المختارة وتم تحليل نتائج الاستجابة الديناميكية التي تم الحصول عليها من تشغيل المنظومة والتي بينت خلال هذا البحث و المجهزة بحساسات نوع ADXL335 (معجل ثلاثي المحاور) والتي ربطت على حواضن ركائز الأعمدة القائدة والمقادة ووصلت بجهاز تحكم دقيق الذيو Arduino mega2560 بدوره يرسل البيانات الى الحاسوب لعرضها بواسطة برنامج متخصص (Sigview) ليحولها الى شكل بياني مفهوم من الترددات وقوة الاهتزاز بصيغة (FFT). النتائج اظهرت الفرق الذي يحدث عند وجود العيب عن النتائج في حالة عمل المنظومة بصورة مستقرة وخالية من العيوب .وبهذه الطريقة يمكن تشخيص ومن ثم معالجة أي عيب يمكن أن يحدث في المنظومة .

الكلمات المفتاحية:- تحليل الاهتزازات ، خوارزمية فورير ، تشخيص عيوب ميكانيكية ، الحالة المثالية للتشغيل .

1. Introduction:

Machines are very essential in our lives and it simplified the people's works. Now machines are becoming more complex, faster, intricate, and delicate and production process that are interlinked and automated. Rotating machinery is a basic part in any industry. In real systems, faults are unavoidable due to the errors and accuracy in manufacturing. Faults may temporarily develop in the system due to the operating conditions such as looseness, heat generation, wear, etc. Failure of the rotor system has safety implications along with economic considerations. Hence, rotating machinery needs to be monitored continuously for the faults. The greatest challenge in the condition monitoring is the diagnosis of a fault before it becomes critical. Pulley-belt application is the major type of rotary machine systems. The Belt is a loop of flexible material used to link two or more rotating shafts mechanically, most often parallel. Belts may be used as a source of motion, to transmit power efficiently. As any rotary machine pulley-belt system have not a few number of faults in general likes:

- belt damage and mismatch
- Pulley eccentricity, imbalance, wobble and misalignment

- bent shaft
- bearing defects and poor lubrication
- Mechanical looseness.....and others.

Dimitris *et.al.*, 2006 practically studied topic of maintenance of mechanical drivers and faults diagnosis of machine elements the results were specialized bearings only by shock pulse and the vibration spectrum analysis methods. The proposed detection technique permits the identification of the precise location of a fault as well as its development in operation condition allowing predictive maintenance tasks. **Gregor *et.al.*, 2009** presented introduction of damping into the flexible multi body belt-drive model, Different damping mechanisms are proposed for the damping of the longitudinal and bending deformations and several experiments were conducted in order to obtain the damping properties. Good agreement between the numerical result and the experimentally obtained data was found. Finally, the applicability of the belt-drive model was presented in a comparison. **Arko *et.al.*, 2011** presented monitoring vibration of a model of rotating machine. The case study was a rotate shaft with balance and unbalance by add and reduce mass of balance, experiment results show the agreement with theory that unbalance condition on a rotating machine can lead to larger vibration amplitude compared to balance condition. Adding and reducing the mass for balancing can be performed to obtain lower vibration level.. **Kumar *et.al.*, 2012** presented determination of unbalance in rotating machine using vibration signature analysis The experimental frequency spectra were obtained for both balanced and unbalanced condition under different unbalanced forces at different speed conditions. This paper aims at the implementation of condition based maintenance on rotating machine. **Ojha *et.al.*, 2014** their study was about performance monitoring of vibration in belt conveyor system, this paper presents the vibration related faults diagnosis and maintenance of belt conveyor system. **Bansal *et.al.*, 2014** deal with monitoring and analysis of vibration signal in turning machine with one type of cutting tool and sample (mild steel and brass). **Pravesh and Akhilesh *et.al.*, 2014** focused on fault diagnosis of ball bearing using time domain analysis and fast Fourier transformation. The result shows that the statistical analysis through different time domain parameters and its fast Fourier transformation provide sefficient representation of fault detection in rolling element bearings **Kokil *et.al.*, 2014** studied detection of fault in rolling element bearing using condition monitoring by experimental approach. This paper Specialized in faults of pulley-belt system, FFT results of some faults which had been invented compared with FFT of healthy operate condition, and from this technique effect of each fault will be known. **Nayak *et.al.*, 2015** Presented design and development of machine fault simulator (MFS) for fault diagnosis. This paper show how to industry and construction of machine contains most parts that get damaged and vibrate over time in plurality machines like motor **Abdulshakoor *et.al.*, 2015** Used vibration analysis for faults in V-belt 13mm, three faults which are used side-cut-out, side-cut-in and loose. (**Mouleeswaran and Moorthy, 2015**) introduced vibration monitoring for defect diagnosis on a machine tool (comprehensive case study). **Algule *et.al.*, 2015** presented an experimental study of unbalance in a shaft rotor system using vibration signature analysis Experimental studies were performed on a rotor to predict the unbalance in rotor. The vibrations were measured at different speeds using FFT. **This paper** specialized in faults of pulley-belt system, FFT results of some faults which had

been invented compared with FFT of healthy operate condition, and from this technique the effect of each fault will be known as peaks in the FFT spectrum graph.

2. Experimental Setup And Vibration Measurement:

Machine system consist of heavy structure steel frame, steel pulleys, DC motor variable speed, shafts, pillow bearings (housing), tachometer and tools for precision measurements as shown in fig (1)

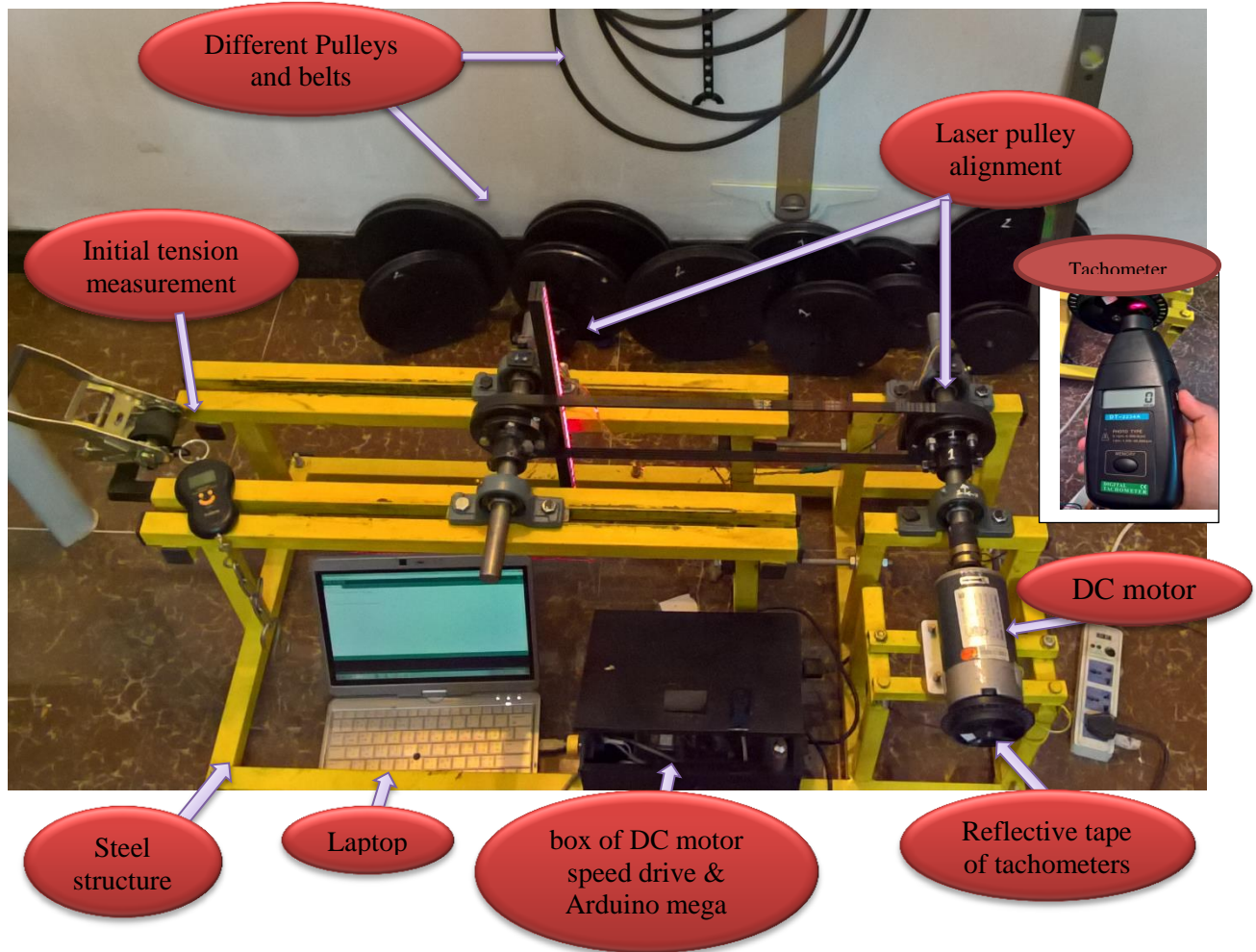


Figure 1. Details of system parts.

Vibration sensors (ADXL335) (3axis accelerometer) with sensitivity of 300 mv/g was used during this work, can read a range of 0.5 Hz to 1600 Hz for the X and Y axes, and a range of 0.5 Hz to 550 Hz for the Z axis output, where sensors mounted geometrically on bearing brackets of drive and driven shafts, Y-direction of sensor will be in axil direction of shaft, X and Z will be radial direction on the shaft horizontal and vertical respectively shown in Fig 2. Sensors connected to Arduino type mega which have CPU 16 MHz is sending the data of vibration after calibration process to the laptop to display it in software model (Sigview) as a time and frequency domain band by FFT (fast Fourier transform). To know the magnitudes of rotate speeds need to rpm gauge (Tachometer DT-2234A) photo type with reflective tape on rotate parts as shown above.

Initial tension should be at a constant value of 30N in each cases, this value determined as installation tension (optimal) by the manufacturing company (Super Star belts), also this magnitude investigated by tensile test device and PID-ANSYS, data of tensioned belt deals as hyper-elastic material by Moony-Revilin model.

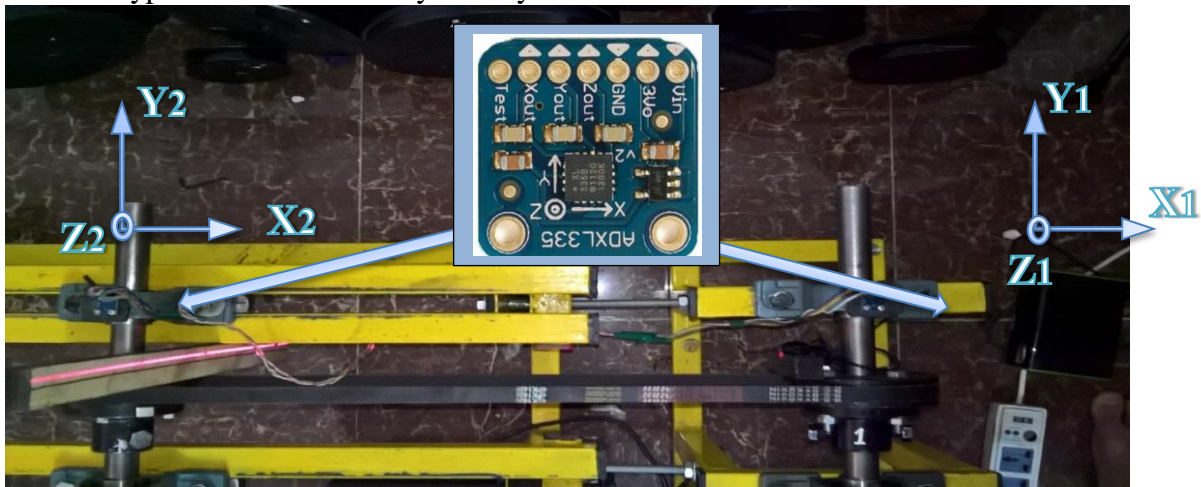


Fig 2.Two sensors ADXL335 geometrically positions as fixed on bearings housings

3. Vibrations analysis

Vibration can be used to detect and diagnose problems on rotating equipment ranging from electric motors to large crushing machines used for mining and processing, because of each part in a case of motion has an individual frequency. FFT has important features to show the frequency for each part, also the frequency of faults which are unavoidable due to the errors and accuracy in manufacturing or may temporarily develop in the system due to the operating conditions. The most encounter faults existing in the pulley belt system described in the following tables [1], axial and radial directions are shown in table(1) and (2) respectively. Having in mind that the fundamental frequency is shaft revolution in rpm 1X.

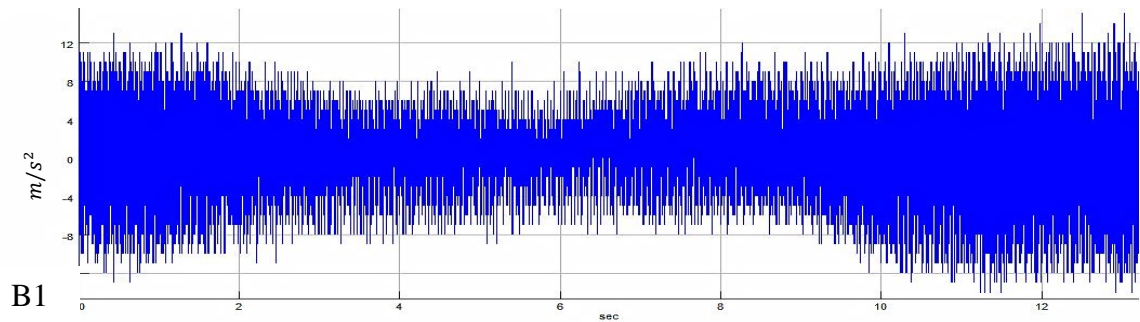
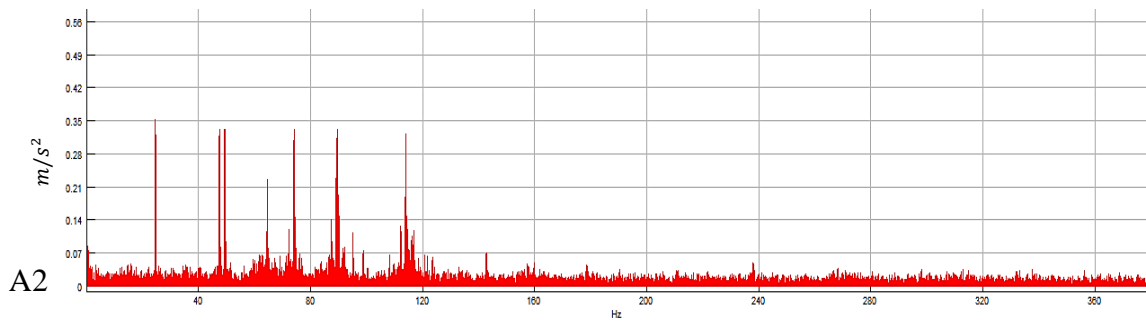
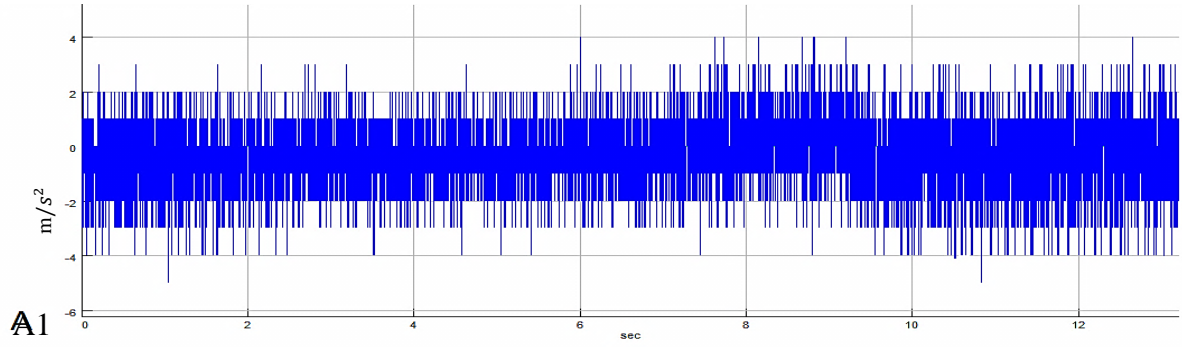
Table (1) common faults cause vibration in the axial direction

	Symptom	Frequency	Description
Axial direction	Overhung unbalance	1X	Overhung pulley cause high 1X in axial direction because unbalance creates a bending moment on the shaft.
	Angular misalignment (coupling)	1X,2X,3X	Expect to see 1X peak in the axial direction, and a small 2X and 3X peak depend upon the linearity of vibration.
	Belt misalignment	1X	Misalignment of pulleys produces high axial vibration at 1X turning speed of each component (drive and driven pulley), misalignment take as offset and angular form.
	Bent shaft	1X,2X	Shaft may bend due to excessive heat or may be physically bent, high 1X axial vibration and 2X if bend is closer to the coupling.
	Cocked bearing inner or outer race	1X,2X,3X	The bearing can be cocked on the shaft or in the housing, which is form of misalignment. Axially peaks will often be seen at 1X, 2X as well as 3X.

Table 2. Most common faults occur in belt-pulley system radial directions.

Radial directions	All forms of unbalance	1X	The wave form will be very sinusoidal in time domain view and high peak of 1X in radial directions (vertical, horizontal). There are types of unbalance like static, couple, dynamic, vertical and overhung unbalance.
	Eccentric pulleys	1X	Eccentricity occurs when the center of rotation is offset from the geometric centerline of pulley. There will be strong 1X in radial component especially in direction parallel to belt. Wave form will be very sinusoidal in time domain view.
	Resonance (structural)	1X	If the natural frequency of the system close to running speed of machine the peak 1X will be high with base elevated. Resonance is amplified from other faults.
	Resonance (belt)	1X	1X board and high peak If the belt natural frequency coincides with rpm of driven pulley. Belt resonance range depends on rpm, length of belt and initial tension.
	Looseness (structural)	1X	This fault caused by weakness in foundation this allows machine vibrate freely in the direction where the weakness is greatest (often horizontal)
	Looseness (rotation-noise)	1X-10X	Looseness in rotating element occur after significant bearing wear and may be observed during four stage. Spectrum will show large number of harmonics from 1X to 10X and cause high noise. If wear reach to severe case 0.5X will appear in spectrum.
	Looseness (pillow block)	1X, 2X, 3X	Peaks of 1X and high 2X in some cases 3X will generated, also sub harmonics (0.5X, 0.3X, 0.25X) may be present.
	Parallel (offset) misalignment (Coupling)	1X, 2X, 3X	If the center lines of shafts are parallel but not coincident. Will cause high peak at 2X than 1X and 3X, these peak will be not equal between vertical and horizontal direction.
	Worn, loose and mismatched belts	$f_b, 2f_b, 3f_b$	peak at belt frequency witness if the belt worm or loose, high peak indicate to the severity of belt fault.
	Bearing elements frequencies	$\text{Belt frequency} = \frac{\pi \times \text{pulley rpm} \times \text{pitch dia.}}{\text{belt length}}$	
		$BPFI = \frac{Nb}{2} (1 + \frac{Bd}{Pd} \cos \theta) \times \text{rpm}$	BPFI. ball pass frequency inner race BPFO. Ball pass frequency outer race FTF. Fundamental train frequency cage BSF. Ball spin frequency. Nb. Number of balls in bearing. Bd. Ball diameter. Pd. Pitch bearing diameter. θ . Angle of ball contact. Vibrations from elements of bearing tend to be localized and not transmitted to other parts of system to discriminate between bearing vibrations and other vibrations, take readings at several locations on the same equipment.
		$BPFO = \frac{Nb}{2} (1 - \frac{Bd}{Pd} \cos \theta) \times \text{rpm}$	
		$FTF = \frac{1}{2} (1 - \frac{Bd}{Pd} \cos \theta) \times \text{rpm}$	
		$BSF = \frac{Pd}{2Bd} \left[1 - \left(\frac{Bd}{Pd} \right)^2 (\cos \theta)^2 \right] \times \text{rpm}$	

To recognize healthy conditions from bad or faulty conditions of operating machines, time domain waveform will be as shown in fig (3). Faulty conditions waveform will give incomprehensible signal and more peaks in FFT at different frequencies. While at good conditions wave form will be consistent and sinusoidal often. While at a good conditions waveform will be consistent, sinusoidal often, and low and low number of peaks in FFT will appear.



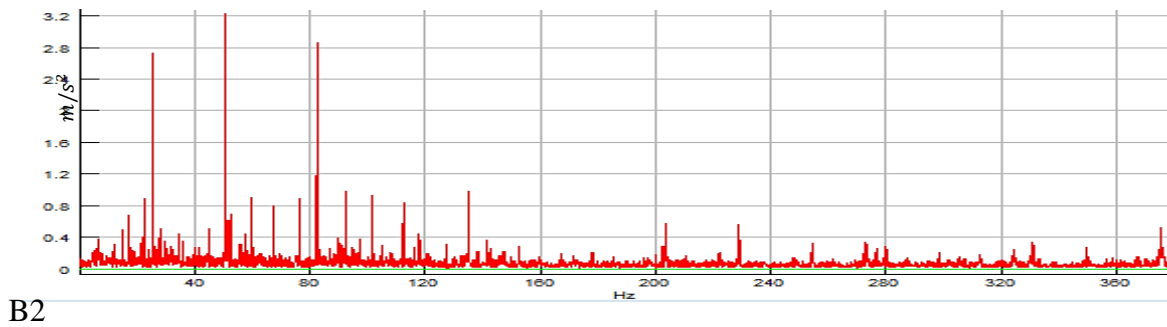


Fig 3, Good condition (A1 time domain waveform, A2 frequency domain), faulty condition (B1 time domain waveform, B2 frequency domain)

4. Methodology of obtaining results.

It is necessary to know the FFT shapes (one sensor three directions) of healthy conditions before make any fault in the system for comparison, and then some of faults Intended to occur. The difference in the shapes and severity of faulty conditions indication of the type of defect. High practical experience will needed because sometimes faults coincide with the same time, like unbalance of pulley and resonance of belt or structure and looseness , each of them will give 1X in radial directions, for instance to recognize balance of pulley it just done by operate pulley without belt, and to check belt resonance, the belt initial tension or RPM will be change. To recognize structure resonance, the type of installation method will be change or add extra weights for installation, .etc. Results will be at the following conditions:

RPM	Initial tension (N)	Center distance (cm)	Drive pulley diameter (cm)	Driven pulley diameter (cm)	Type of belt
1500	30	37	10	10	V13

5. Results

5.1 Optimal condition.

In the vibration analysis technique diagnosis of any defect based on the difference of FFT graphs between the optimal condition operation and the condition of faulty operation. The system work at optimal condition when there is no any unfavorable source of vibration caused by defects, FFT graphs at all directions of this condition does not contain any abnormal high peaks. The figure below is a result of operation system takes carefully into account avoidance the faults as much as possible.

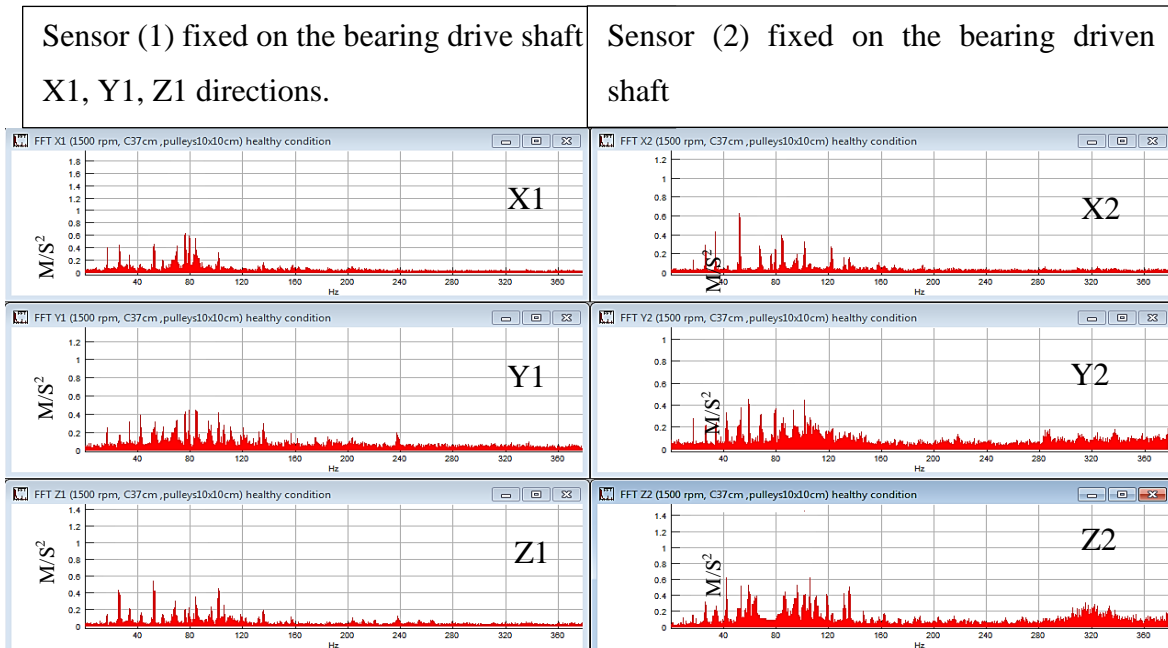


Fig.4, FFT of optimal operate system condition

5.2 Unbalance fault.

FFT of unbalance pulleys operate system, unbalance masses cause centrifugal force, in FFT spectrum unbalance force cause high peak at 1X (25Hz) . figure (5) shows process of add magnetic piece which generate centrifugal force in each pulleys.

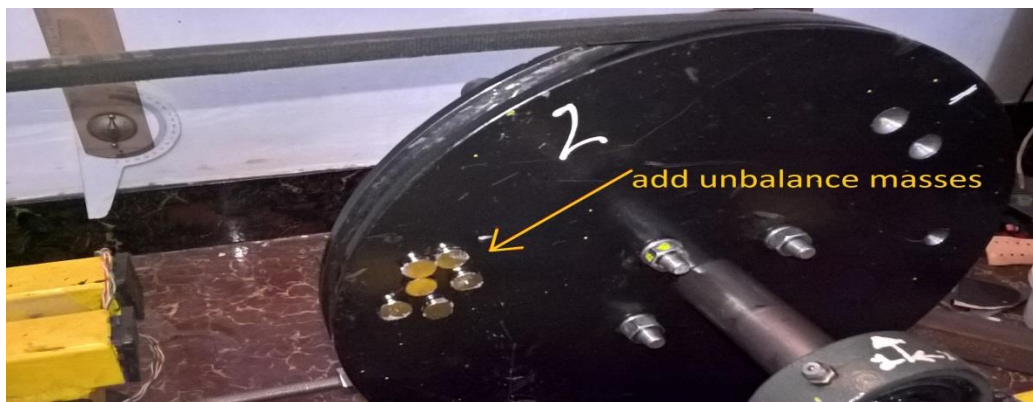


Figure 5, adding unbalance mass on the one direction of balancing pulley

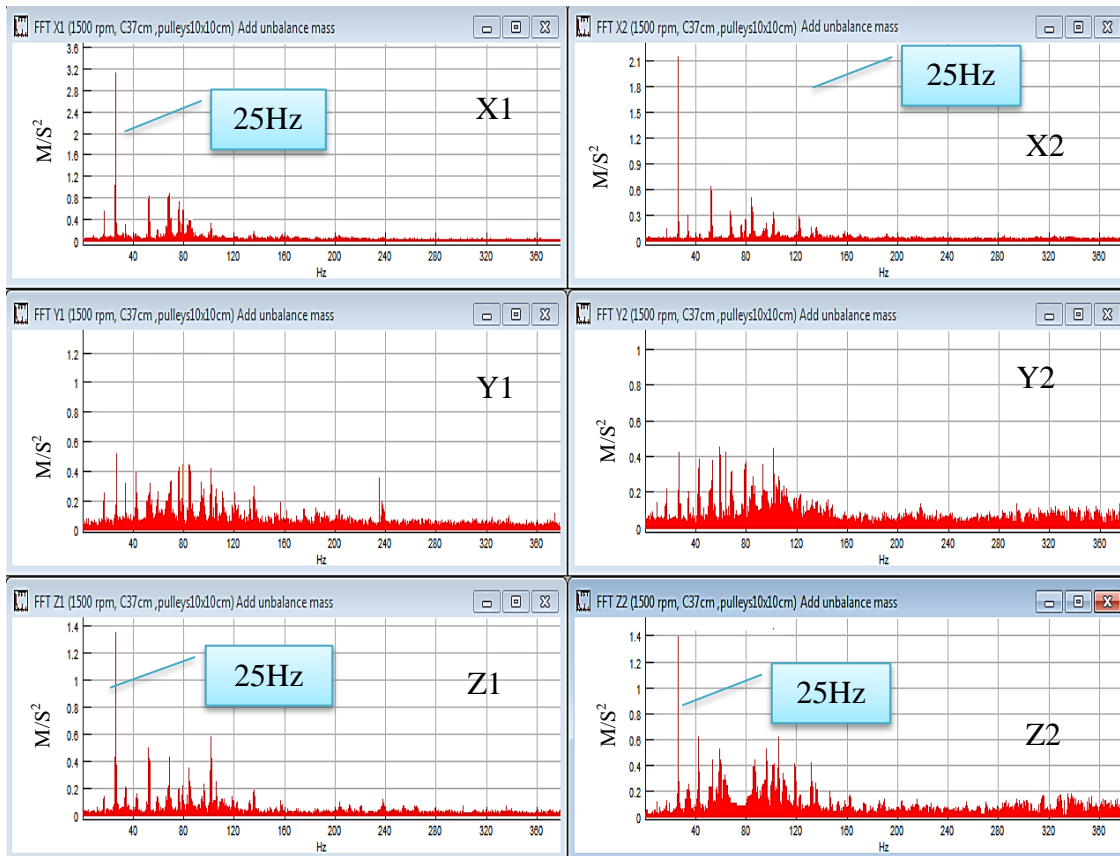


Figure 6, FFT results of unbalance condition

5.3 Belt misalignment (offset pulleys).

FFT of belt-misalignment operate system shows high 1X peak in the axial (Y_1 , Y_2) directions. Figure (7) shows sheaves parallel misalignment.



Figure (7) shows sheaves parallel misalignment

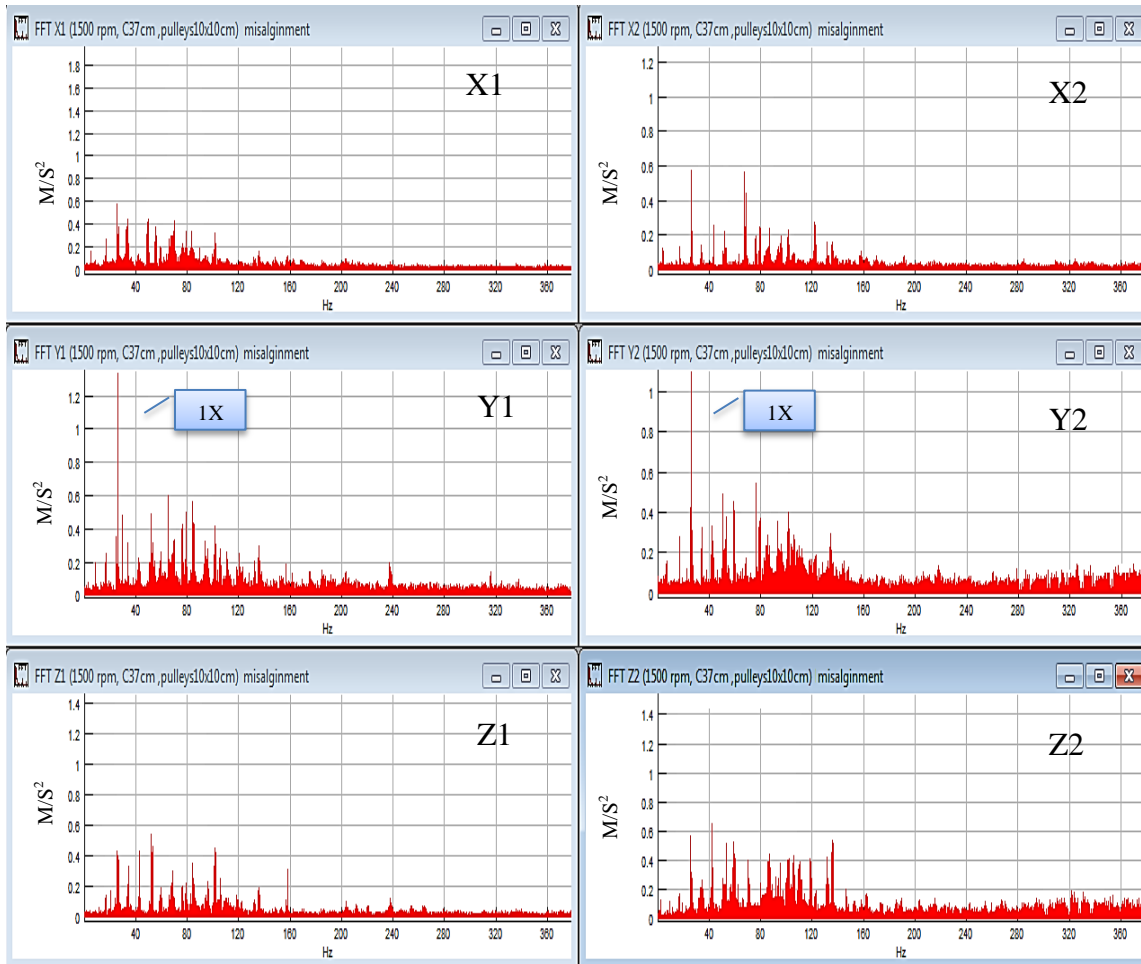


Figure 8, FFT results of parallel misalignment condition

5.4 Belt worn

FFT of belt-damages operate system. at conditions of: 30N initial tension, 1500 rpm (25 Hz), 25x25 cm pulleys diameters, and center distance 37 cm. belt damaged as shown below by side-cut out. FFT graph show peaks at (1fb, 2fb, 3fb....) and peaks depend on the shape of damage.



Figure 9, belt-damages shape

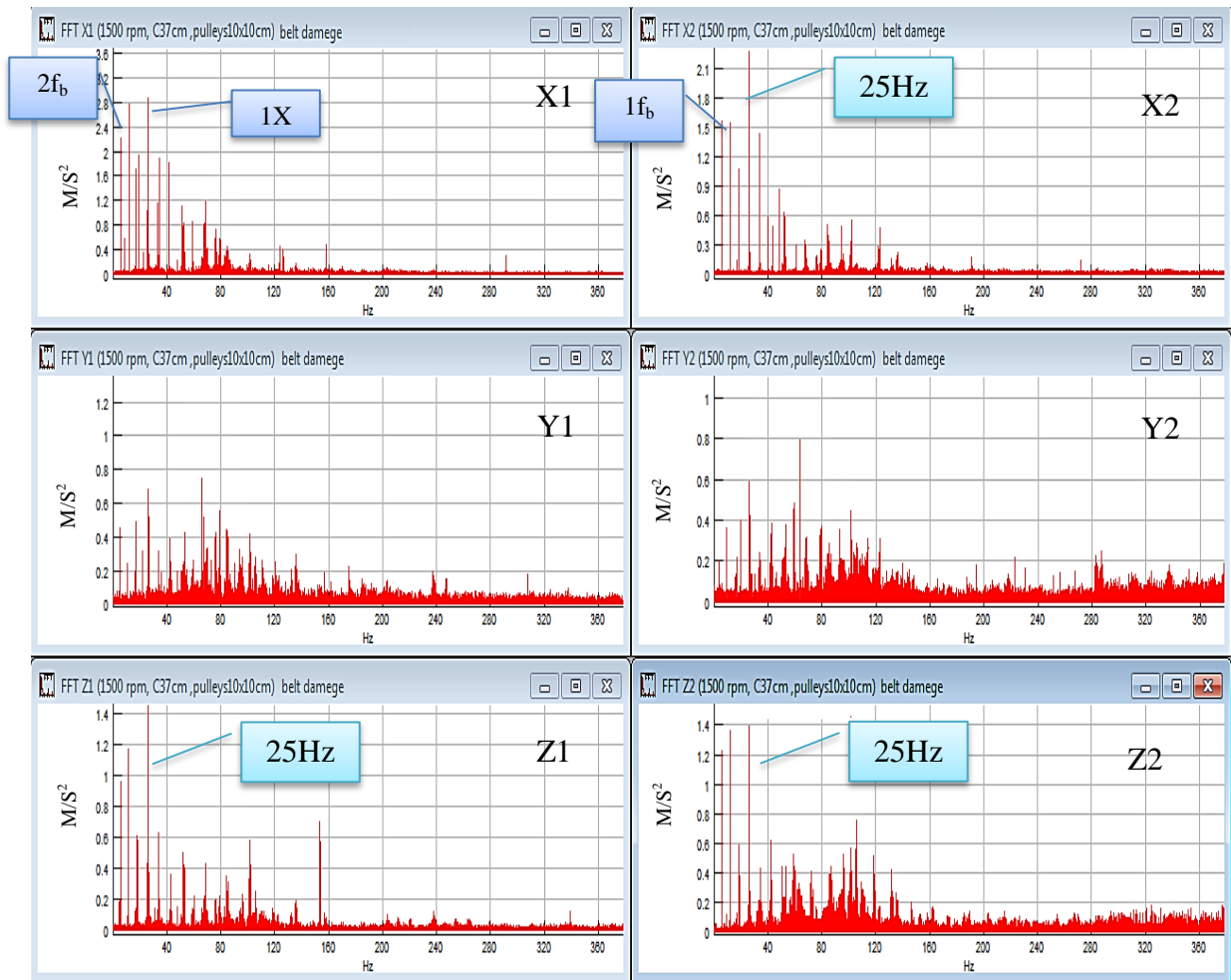


Figure 10, FFT results of belt-damage condition

5.5 Belt resonance.

FFT of belt-resonance state shows high peaks at 1X in the radial directions. 18N initial tension, almost 1500 rpm (25Hz), 10x10 cm pulleys diameters, and center distance 37 cm. figure below of stroboscope camera picture shows belt resonance state.



Fig 11, stroboscope camera picture shows belt resonance

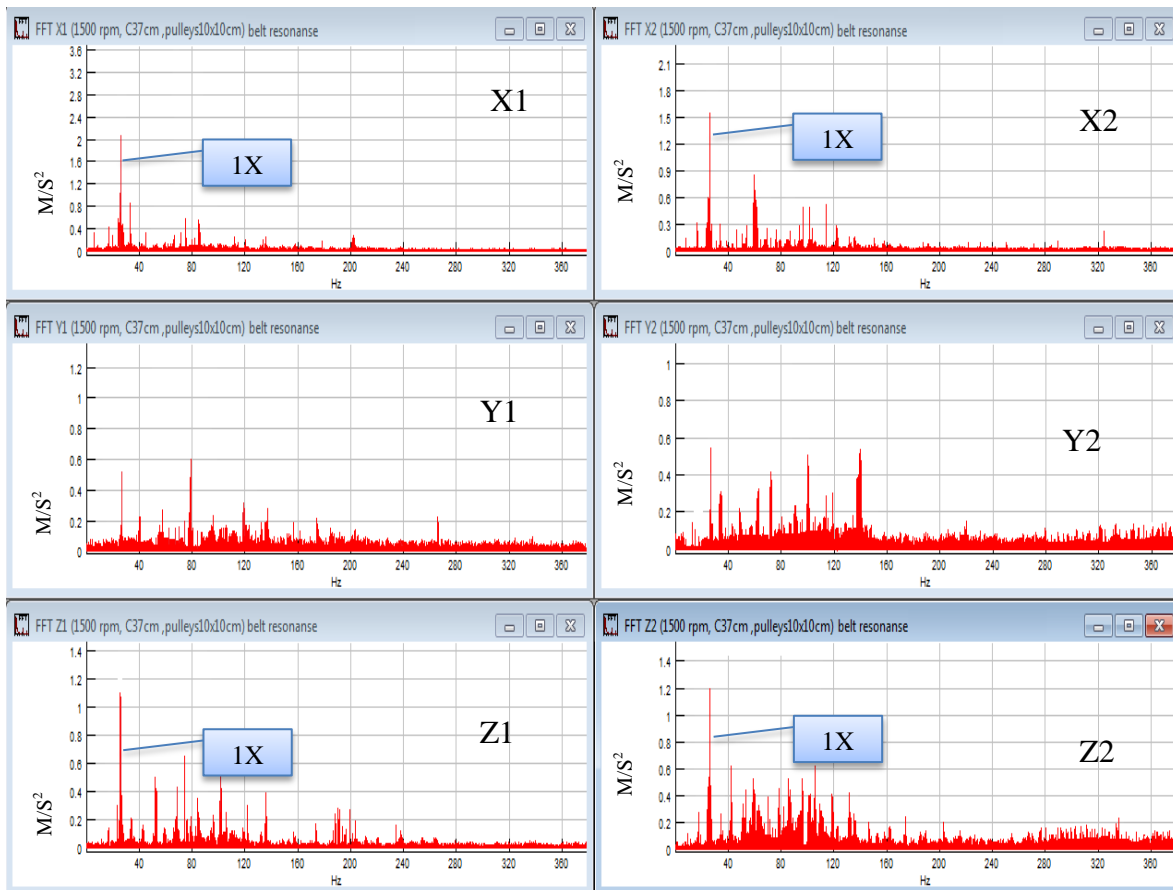


Figure 10, FFT results of belt-resonance condition

6. Conclusion

In this paper, it is concluded that the time domain and its statistical analysis only predict the fault. It was never say about the fault origin with the help of time domain analysis. But the frequency domain analysis gives the fault position accurately. Pulleys had been balanced and after making sure that the system does not contain any defects, healthy condition Figure (4) showed small peeks (low than 1 unit amplitude).fault making in unbalance condition by adding small masses (strong magnetics) at one centrifugal direction, will increase vibration in radial directions at peak 1X (1500rpm or 25 Hz) see Figure (5), the high of peak increases by add more masses because increasing in center fugal force.

In case of offset sheaves misalignment fault Fig (6), axial vibration generates in FFT peak at 1X and there are small incidental changes in radial directions.

Fig (7) shows FFT of belt damage fault case peeks at belt rate, the number of generated peaks and they heights depends on shapes of damages, graph figure showed results of inner side cut belt fault, and:

$$belt\ rate = \frac{\pi \times 1500 \times 0.1}{60 \times 1.225} = 6.4\ Hz . \quad \therefore \quad 1fb=6.4Hz , 2fb=12.8Hz , 3fb=19.2Hz.....$$

Where: 1.225mm is the length of belt.
0.1m pitch diameter of pulleys.
1500 rpm rotating speed by (tachometer gauge).

In a case of belt resonance the fault is made by reduce initial tension to 18N which lead to increase belt vibrations in case of resonance between the natural frequency of belt and rotating speed, the peak shows in figure(8) in radial directions and it board at the base. It can also see belt resonance state clearly by use Mobile android application “Stroboscope camera” which takes short video and converted to a huge numbers of pictures, resonance in the belt depends on RPM, belt tensions, and center distance.

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